Applied Radiation and Isotopes 136 (2018) 82–86

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Determination of transmission factors in beta radiation beams

Ivón Oramas Polo*, Linda V.E. Caldas

Instituto de Pesquisas Energéticas e Nucleares/ Comissão Nacional de Energia Nuclear, IPEN/CNEN. Av. Prof. Lineu Prestes, 2242 - 05508-000, São Paulo, SP, Brazil

ARTICLE INFO

Keywords:
Transmission factors
extrapolation chamber
beta radiation
BSS2

ABSTRACT

In beta emitters, in order to evaluate the absorbed dose rate at different tissue depths, it is necessary to determine the transmission factors. In this work, the transmission factors determined in beta secondary standard radiation beams are presented. For this purpose, an extrapolation chamber was used. The results obtained were considered acceptable, and they are within the uncertainties in comparison with the values provided by the source calibration certificate. The maximum differences between the results obtained in this work and those from the calibration certificate were 3.3%, 3.8% and 5.9% for ^{90}Sr/^{90}Y, ^{85}Kr and ^{147}Pm sources respectively.

1. Introduction

In activities close to open and small radioactive beta-gamma sources, the dose rate due to beta radiation is often unexpectedly high. When a volume of matter is exposed to beta and to gamma radiation of the same fluence, the dose rate by beta radiation is considerably higher than the dose rate by gamma radiation (Caldas, 1980).

Beta radiation is a weakly penetrating radiation. The skin is the organ that most frequently receives significant doses. It is considered the basal layer of epidermis and its cells are at a shallow depth (Pook and Francis, 1975; ICRU, 1997). Beta particles cause ionization throughout their trajectory and because that radiation is easily absorbed, in the external irradiation, the highest dose is located at the skin surface (Caldas, 1980).

The standard ISO 6980–2 describes the calibration methods of the basic quantities that characterize the beta radiation fields (maximum energy of 0.066–3.54MeV) (ISO, 2004).

For calibration of beta sources and detectors, the transmission factors in the tissue must be determined (Böhm, 1986). Transmission factors are the factors, which give the change in dose rate with transmission through a range of tissue thicknesses (Owen, 1973). The transmission factors can be represented in the depth–dose curve (ISO, 2004; Brunzendorf, 2012a, 2012b). They are very important for the determination of the absorbed dose rates at different tissue depths. To determine the transmission factors, the ionization current for different absorber thicknesses must be measured (I_a). Subsequently, this current is extrapolated to a null thickness representing the skin surface (I_0). The transmission factor is the ratio of the current I_a and the current I_0 (Caldas, 1980; Antonio et al., 2014).

Some transmission factors have been determined for the Beta Secondary Standard (BSS) sources (Owen, 1973; Pook and Francis, 1975; Heinzelmann, 1975; Caldas, 1980; Böhm, 1986; Antonio et al., 2014). These standards did not use the ^{85}Kr source. This source started to be used instead of the ^{204}Tl source in the BSS2 secondary standard, because the energy spectra of the beta particles are similar, but the half-life of ^{85}Kr (10.756 years) is more convenient than that of ^{204}Tl (3.78 years) (BSS2, 2005; ISO, 2004). The ISO (2004) shows depth-dose curves measured at the calibration distance established for different sources. Brunzendorf (2012a) presented a method to determine the transmission factors for beta dosimetry. Additionally, this author published for the first time the complete depth–dose curves of the series 1 beta radiation fields of all BSS2 sources (2012b). The transmission factors for the ^{85}Kr source were calculated using an extrapolation chamber reported by Reynaldo (2015).

The objective of this work was to determine the transmission factors for the BSS2 beta radiation beams. The results were compared with the transmission factors of the source calibration certificates. In addition, the associated uncertainties of the transmission factors were calculated. The results of this work are of great importance for the Laboratory for Calibration of Instruments of Institute of Nuclear and Energy Research (LCI/IPEN) in the establishment of a primary radiation standard.

2. Materials and methods

2.1. PTW extrapolation chamber and beta radiation sources

In this work, a commercial extrapolation chamber Physikalisch-Technische Werkstätten Freiburg, PTW type 23392, of the LCI/IPEN was used. It was developed by Böhm (1986), and built by PTW. It is considered as the primary standard for the determination of the beta

---

* Corresponding author.
E-mail addresses: ivonoramas67@gmail.com (I.O. Polo), lcaldas@ipen.br (L.V.E. Caldas).

https://doi.org/10.1016/j.apradiso.2018.02.010
Received 28 November 2017; Received in revised form 24 January 2018; Accepted 8 February 2018

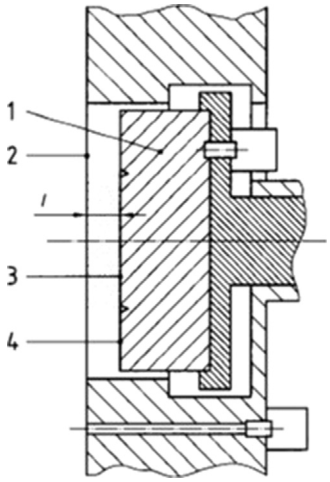

Fig. 1. Cross section of an extrapolation chamber. Main components: 1: piston, 2: entrance window, 3: collecting electrode, 4: guard ring, l: chamber depth (ISO, 2004).

Table 1
Main characteristics of the BSS2 beta sources.

Characteristic	Radionuclide		
	^{147}Pm	^{85}Kr	^{90}Sr/^{90}Y
Nominal activity	3.7 GBq	3.7 GBq	460 MBq
Mean beta energy (MeV)	0.06	0.24	0.8
Calibration distance (cm)	20	30	11, 20, 30, 50
Calibration date	19/11/2004	30/11/2004	19/11/2004
Approximate half-life (days)	958	3915	10483

Fig. 2. Extrapolation chamber entrance window covered by a Hostaphan absorbing sheet.

radiation absorbed dose rates in tissue (Böhm, 1986). Fig. 1 shows a cross section view of the Böhm extrapolation chamber. The collecting electrode, the guard ring, a PMMA block and the entrance window constitute its main components.

Charge measurements with this extrapolation chamber were taken with a Keithley model 6517B electrometer.

For the development of this work, the BSS2 sources were utilized. The main characteristics of these sources are shown in Table 1 (BSS2, 2005; PTB, 2005a, 2005b, 2005c).

The calibration distance used for the ^{90}Sr/^{90}Y source was 11 cm. For use of the ^{85}Kr and the ^{147}Pm sources in the BSS2 system, a Polyethylene Terephthalate (Hostaphan) filter must be used. At the distance of 11 cm, the ^{90}Sr/^{90}Y source was not calibrated with a filter (BSS2, 2005)

2.2. Determination of transmission factors

In order to determine the transmission factors, the extrapolation chamber was covered by thin sheets of different thicknesses (Caldas, 1980). These sheets were made of a material equivalent to the tissue, and they shall be placed as close as possible to the chamber entrance window (Owen, 1973). Tissue-equivalence is the property of a material which mass stopping power and the diffusion properties of the radiation are identical to those of the tissue. The material of the absorber sheets is Polyethylene Terephthalate, commercially known as Hostaphan, with density of 1.40 g/cm^3. To determine the transmission factors, an equivalence ratio between the material of the absorber sheets and the ICRU tissue must be used. The relationship between the Hostaphan and the ICRU tissue is 10.8 mg/cm^2 of Hostaphan = 10.0 mg/cm^2 of tissue (Owen, 1973).

In addition, it is necessary to convert the surface density of the chamber entrance window to the tissue. For each absorbing sheet, the following expression was used for the determination of total thickness (depth) in ICRU tissue (Antonio, 2013):

$$t_T = (d_j*c_j)+(e_H*\rho_H*c_H) \tag{1}$$

where d_j is the thickness of the absorbing sheet that is equivalent to the tissue; c_j is the conversion coefficient of the material of the chamber entrance window to the tissue; e_H is the thickness of the absorbing sheet; ρ_H is the volumetric density of the absorbing sheet, and c_H is the conversion coefficient of the material of the absorbing sheet to the tissue.

As previously mentioned, the transmission factor is the ratio of currents I_a and I_0:

$$T' = I_a/I_0 \tag{2}$$

Taking into account the source-detector distance and the thickness of the absorbing sheet, a correction factor k_a shall be introduced:

$$k_a = (a - a_1)^2/a_1 \tag{3}$$

where a is source-detector distance and a_1 is the absorbing sheet thickness.

Finally, transmission factors can be determined by the final expression:

$$T = T'*k_a \tag{4}$$

According to Caldas (1980), the values of T are plotted as a function of surface density.

Every current measurement is referred to air density ρ_0 = 1.1995 kg/m^3 at the reference conditions (air temperature T_0 = 293.15 K, air pressure p_0 = 101.3 kPa). The ionization current must be corrected by the factor k_{TP}, to correct the air density under conditions of the laboratory measurement to reference conditions. The factor k_{TP} con be determined by the expression:

$$k_{TP} = p_0*T/p*T_0 \tag{5}$$

where T is the absolute temperature and p is the air pressure.

Through a computer program, the curve is fitted, and an equation is obtained. From this equation, the transmission factors corresponding to the surface densities that appear in the beta source calibration certificate can be determined. Subsequently, the values obtained experimentally are compared with the values of the calibration certificate.

The chamber entrance window was covered with 8 Hostaphan absorbing sheets, identified as RN 8, RN 25, RN 36, RN 50, RN 75, RN 100, RN 250 and RN 300 for ^{90}Sr/^{90}Y and ^{85}Kr sources. The number corresponds to the sheet thickness in microns. In addition, for the ^{90}Sr

Table 2
Example of the determination of the transmission factor uncertainty for RN 8 absorber for the $^{90}Sr/^{90}Y$ source.

Quantity	Value x	Standard uncertainty u(x) k = 1	Sensitivity coefficient c(x)	Uncertainty contribution u(x) = u(x)*c(x)
k_a	0.999	0.020	1.0031	0.020
T'	1.0031	0.0004	0.999	0.0004
T	1.002			0.020

$/^{90}Y$ source, the entrance window was covered with Polymethyl Methacrylate (PMMA) absorbing plates; once with a 1 mm plate and then with 2 plates together to achieve a thickness of 2 mm. In the case of the ^{147}Pm source, only the RN 8 and RN 25 sheets were used due to the short range of this low energy radiation source, and also 2 sheets of aluminized Mylar of 0.022 mm and 0.010 mm were used. Fig. 2 shows the extrapolation chamber entrance window covered by a Hostaphan absorbing sheet.

The uncertainty of the transmission factor for each absorber thickness was determined according to the following expression:

$$u_c^2 = \sum_{i=1}^{N} [c_i u(x_i)]^2 \tag{6}$$

where u_c is the combined uncertainty; c_i is the sensitivity coefficient and $u(x_i)$ is the uncertainty contribution (INMETRO, 2012).

Table 2 shows an example of the determination of the uncertainties for one of the absorbers (RN 8) used in the measurement of the transmission factor for the $^{90}Sr/^{90}Y$ source.

3. Results and discussion

To determine the transmission factors of the $^{90}Sr/^{90}Y$ and the ^{85}Kr sources, the extrapolation chamber was positioned at the source-detector distances of 11 cm and 30 cm respectively. The bias voltage and the chamber depth were maintained at ± 25 V and 2.5 mm, respectively. In the case of the ^{147}Pm source, the source-detector distance was 20 cm, the voltage was ± 10 V and the chamber depth was 1 mm.

The ionization current was measured with and without the absorbering sheets. Every ionization current was corrected by the k_{Tp} factor. The ionization current varied in the range of (4.961 ± 0.003) pA and (3.8438 ± 0.0022) pA with a coefficient of variation less than 0.07% for the $^{90}Sr/^{90}Y$ source. For the ^{85}Kr source, the current varied in the range of (1.0950 ± 0.0012) pA and (0.5488 ± 0.0007) pA with a coefficient of variation less than 0.41%. For the ^{147}Pm source, the current varied in the range of (11.28 ± 0.24) x 10^{-3} pA and (5.85 ± 0.24) x 10^{-3} pA with a coefficient of variation less than 8.10%. The current I_0 was obtained by fitting the curve of the ionization current versus the surface density in the tissue. A computer program fitted polynomials to the curve points. A third degree polynomial was obtained adequate to fit the experimental values for the $^{90}Sr/^{90}Y$ and the ^{85}Kr sources and an exponential fitting was adequate for the ^{147}Pm source. The current values of I_0 were: (4.9865 ± 0.0011) pA, (1.0999 ± 0.0011) pA and (15 ± 5) x 10^{-3} pA for $^{90}Sr/^{90}Y$, ^{85}Kr and ^{147}Pm sources respectively.

From the current value I_0, it was possible to determine the transmission factors T', the coefficient k_a and the transmission factors T for the sources. These values are shown in Table 3.

From the values for the transmission factors of Table 3, curves were obtained to determine the transmission factors for the tissue-equivalent

Table 3
Transmission factors for the BSS2 sources.

1	2	3	4	5
	0.67	0.9949 ± 0.0007	1.0000 ± 0.0200	0.995 ± 0.020
		$^{90}Sr/^{90}Y$		
		Material: Hostaphan		
RN 8	1.70	1.0012 ± 0.0004	0.9999 ± 0.0200	1.001 ± 0.020
RN 25	3.91	1.0213 ± 0.0004	0.9997 ± 0.0200	1.021 ± 0.020
RN 36	5.33	1.0343 ± 0.0007	0.9993 ± 0.0200	1.034 ± 0.021
RN 50	7.15	1.0506 ± 0.0007	0.9991 ± 0.0200	1.050 ± 0.021
RN 75	10.39	1.0622 ± 0.0005	0.9986 ± 0.0200	1.061 ± 0.021
RN 100	13.63	1.0880 ± 0.0005	0.9982 ± 0.0200	1.086 ± 0.022
RN 250	33.07	1.1487 ± 0.0006	0.9955 ± 0.0200	1.144 ± 0.023
RN 300	39.56	1.1569 ± 0.0005	0.9946 ± 0.0200	1.151 ± 0.023
		Material: PMMA		
1 mm	135.31	1.0855 ± 0.0008	0.9819 ± 0.0200	1.066 ± 0.022
2 mm	269.92	0.7708 ± 0.0005	0.9640 ± 0.0201	0.743 ± 0.015
		^{85}Kr		
		Material: Hostaphan		
	0.67	0.9956 ± 0.0011	1.0000 ± 0.0200	0.996 ± 0.020
RN 8	1.70	0.9936 ± 0.0013	0.9999 ± 0.0200	0.994 ± 0.020
RN 25	3.91	0.983 ± 0.004	0.9999 ± 0.0200	0.983 ± 0.020
RN 36	5.33	0.9632 ± 0.0011	0.9998 ± 0.0200	0.963 ± 0.019
RN 50	7.15	0.951 ± 0.004	0.9997 ± 0.0200	0.950 ± 0.019
RN 75	10.39	0.9114 ± 0.0009	0.9995 ± 0.0200	0.911 ± 0.018
RN 100	13.63	0.8561 ± 0.0014	0.9993 ± 0.0200	0.856 ± 0.017
RN 250	33.07	0.5701 ± 0.0012	0.9983 ± 0.0200	0.569 ± 0.011
RN 300	39.56	0.4990 ± 0.0007	0.9980 ± 0.0200	0.498 ± 0.010
		^{147}Pm		
	0.67	0.73 ± 0.25	1.0000 ± 0.0200	0.73 ± 0.25
Mylar 1	1.35	0.66 ± 0.23	0.9999 ± 0.0200	0.66 ± 0.23
RN 8 Hostaphan	1.70	0.60 ± 0.21	0.9999 ± 0.0200	0.60 ± 0.21
Mylar 2	2.28	0.52 ± 0.18	0.9998 ± 0.0200	0.52 ± 0.18
RN 25 Hostaphan	3.91	0.38 ± 0.13	9995. ± 0.0200	0.38 ± 0.13

1. Absorber sheet
2. Surface density of tissue (mg/cm^2)
3. Transmission factor T'
4. Correction factor for source - detector distance K_d
5. Transmission factor T

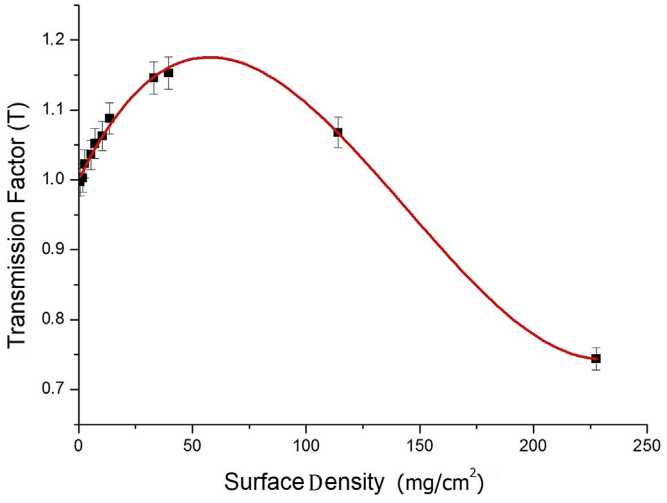

Fig. 3. Final curve of the transmission factors corresponding to the ^{90}Sr/^{90}Y source (Third-order polynomial fitting).

surface densities presented in the calibration certificates of the sources. The curves were fitted according to the same criteria of the curve fitting for the I_0 current.

Figs. 3, 4 and 5 show the final curves for the transmission factor of the ^{90}Sr/ ^{90}Y, ^{85}Kr and ^{147}Pm sources respectively. Table 4 presents the final transmission factors determined in this work. The surface densities of the tissue corresponding to the thicknesses of the source calibration certificates of the sources were taken into account. The factors were normalized to the standard thickness of 0.07 mm. The uncertainties were determined, and the coefficient k = 2.

In the case of the ^{90}Sr /^{90}Y source, it can be observed in Fig. 3 that initially, the curve increases due to the build-up effect. This effect is caused by the secondary electrons scattered on the absorbing sheets. After the curve reaches a maximum, it shows a decrease due to the attenuation of the radiation. In the case of the ^{85}Kr and ^{147}Pm sources, the curves in Figs. 4 and 5 show a decreasing exponential behavior, and the curve of ^{147}Pm drops much faster than in the other source cases.

The uncertainties of the measurements obtained for a primary beta standard depend on the source type, the source activity, and the source-detector distance (Böhm, 1986). In the case of the ^{147}Pm source, the uncertainties of the values of the final transmission factors were relatively high due to the very low source activity. The initial activity of the source was 3.7 GBq (PTB, 2005b). During the present measurements, this source had an activity of only 0.14 GBq.

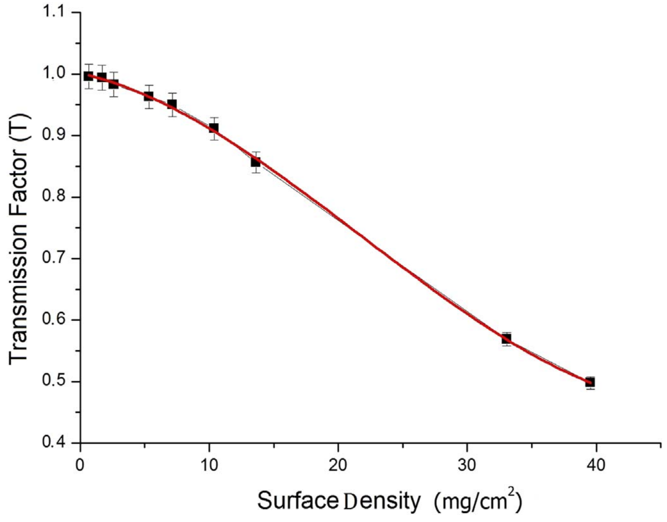

Fig. 4. Final curve of the transmission factors corresponding to the ^{85}Kr source (Third-order polynomial fitting).

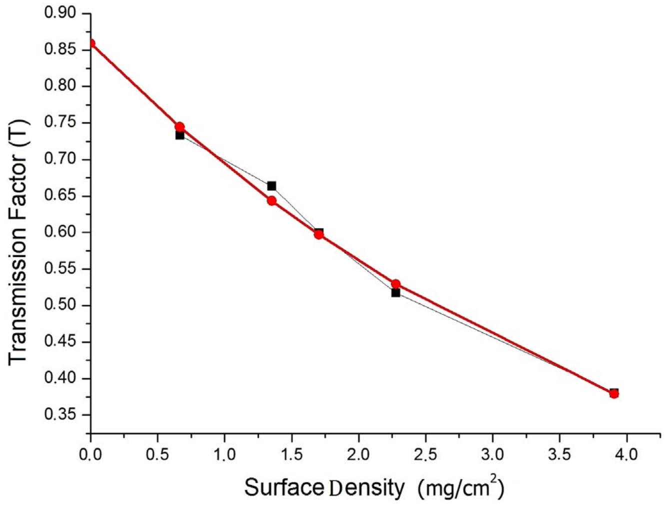

Fig. 5. Final curve of the transmission factors corresponding to the^{147}Pm source (Exponential fitting). The red dots in the graph were only indicated for visualization of the fitted curve.

Reynaldo (2015) presented differences in the determination of transmission factors for the ^{90}Sr/^{90}Y source of 3% for a chamber depth up to 0.20 mm, and for larger depths, the difference reached 10%. For the ^{85}Kr source, the maximum difference was 2.6% for chamber depths greater than 0.05 mm, and for smaller chamber depths, the difference was 5.4%. For the ^{147}Pm source, the differences were between 11% and 34%.

The transmission factors in tissue obtained in this work are in agreement with the values of the transmission factors of the PTB calibration certificates (PTB, 2005a, 2005b, 2005c). The maximum

Table 4

Final transmission factors for the BSS2 sources and certain values of tissue thickness, normalized for the standard thickness of 0.07 mm.

1	2	3	4	5
		^{90}Sr/^{90}Y		
0	0	0.961 ± 0.011	0.93 ± 0.01	3.3
0.02	2	0.973 ± 0.012	0.96 ± 0.01	1.3
0.04	4	0.984 ± 0.014	0.98 ± 0.01	0.4
0.05	5	0.990 ± 0.015	0.99 ± 0.01	0
0.07	7	1.000 ± 0.017	1.00	0
0.10	10	1.015 ± 0.021	1.02 ± 0.01	0.5
0.20	20	1.06 ± 0.04	1.07 ± 0.01	0.9
0.50	50	1.13 ± 0.10	1.11 ± 0.01	1.8
1.00	100	1.11 ± 0.26	1.08 ± 0.01	2.8
		^{85}Kr		
0	0	1.06 ± 0.06	1.05 ± 0.01	0.9
0.02	2	1.05 ± 0.06	1.04 ± 0.01	0.9
0.04	4	1.03 ± 0.06	1.03 ± 0.01	0
0.05	5	1.02 ± 0.06	1.02 ± 0.01	0
0.07	7	1.00 ± 0.06	1.00	0
0.10	10	0.96 ± 0.06	0.96 ± 0.01	0
0.20	20	0.81 ± 0.06	0.78 ± 0.01	3.8
		^{147}Pm		
0	0	4.9 ± 4.4	4.84 ± 0.05	1.6
0.02	2	3.1 ± 2.9	3.12 ± 0.03	0
0.04	4	1.9 ± 1.9	2.00 ± 0.02	1
0.05	5	1.6 ± 1.7	1.59 ± 0.02	0.6
0.07	7	1.00 ± 1.21	1.00	0
0.10	10	0.5 ± 0.7	0.48 ± 0.02	5.9

1. Tissue thickness (mm)
2. Surface density (mg/cm^2)
3. Experimental transmission factor
4. Calibration certificate transmission factor
5. Difference (%)

differences between them were 3.3%, 3.8% and 5.9% for ^{90}Sr/ ^{90}Y, ^{85}Kr and ^{147}Pm sources respectively. Only a small deviation can be seen. The results show that the transmission factors do not change significantly over time, which show the stability of the sources. In the case of ^{147}Pm, despite the enhanced uncertainties, the transmission factors presented only 5.9% as a maximum of difference with respect to the values of the calibration certificate. Measurements with the ^{147}Pm source are more difficult than with the other beta emitters with higher energy.

4. Conclusions

In this work, the transmission factors in standard beta radiation beams were determined using an extrapolation chamber. The agreement among the transmission factors obtained in this work and those from the PTB calibration certificates show that the results are suitable for the establishment of a primary standard for beta radiation at the LCI/IPEN using the PTW extrapolation chamber.

Acknowledgments

The authors thank the partial financial support of the Brazilian funding agencies CNPq (Project numbers: 142297/2015-1, fellowship of I.O. Polo and 301335/2016-8), FAPESP (Project number: 2008/57863-2) and MCTIC: INCT Project: Radiation Metrology in Medicine (Project number: 573659/2008-7).

References

Antonio, P.L., 2013. Establishment of Primary Standardization and Relative Methods with the Use of Luminescent Techniques in Beta Radiation Dosimetry. Ph.D. Thesis. Institute of Nuclear and Energy Research /Sao Paulo University (In Portuguese).

Antonio, P.L., Xavier, M., Caldas, L.V.E., 2014. Determination of transmission factors in tissue using a standard extrapolation chamber. Radiat. Phys. Chem. 95, 38–43.

Böhm, J., 1986. The National Primary Standard of the PTB for Realizing the Unit of the Absorbed Dose Rate to Tissue for Beta Radiation. Physikalisch-Technische Bundesanstalt, Braunschweig, Germany (PTB-Dos-13).

Brunzendorf, J., 2012a. Determination of depth-dose curves in beta dosimetry. Radiat. Prot. Dosim. 151 (2), 203–210.

Brunzendorf, J., 2012b. Depth-dose curves of the beta reference fields ^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y produced by the beta secondary standard BSS2. Radiat. Prot. Dosim. 151 (2), 211–217.

BSS2, 2005. Beta Secondary Standard 2. Operation Manual, QSA Global GmbH. Germany.

Caldas, L.V.E., 1980. Some Calibration and Dosimetry Methods for Beta Radiation. Ph.D. Thesis. Physics Institute/São Paulo University (In Portuguese).

Heinzelmann, M., 1975. Letter: conversion of beta-ray dose rates measured in air to dose rates in skin (Letter). Phys. Med. Biol. 20 (5), 841–843.

ICRU, 1997. International Commission on Radiation Units and Measurements. Dosimetry of External Beta Rays for Radiation Protection. Report 56, USA.

INMETRO, 2012. Evaluation of measurement data – An introduction to the Guide to the expression of uncertainty in measurement – GUM 2008. INMETRO/CICMA/SEPIN. (In Portuguese).

ISO, 2004. International Organization for Standardization. Nuclear Energy – Reference Beta-particle Radiation – Part 2: Calibration Fundamentals Related to Basic Quantities characterizing the Radiation Fields. Genève: ISO, 2004 (ISO/FDIS6980-2:2004).

Owen, B., 1973. Factors for converting beta-ray dose rates measured in air to dose rates in tissue. Phys. Med. Biol. 18, 355–368.

Pook, E.A., Francis, T.M., 1975. Conversion of beta-ray dose rates measured in air to dose rates in skin. Phys. Med. Biol. 20, 147–149.

PTB, 2005a. Physikalisch-technische Bundesanstalt. Calibration certificate of ^{85}Kr source. PTB-6.34-BSS2_04, Braunschweig.

PTB, 2005b. Physikalisch-technische Bundesanstalt. Calibration certificate of ^{147}Pm source. PTB-6.34-BSS2_04, Braunschweig.

PTB, 2005c. Physikalisch-technische Bundesanstalt. Calibration certificate of ^{90}Sr + ^{90}Y source.PTB-6.34-BSS2_04, Braunschweig.

Reynaldo, S. R., 2015. Characterization of an Extrapolation Chamber as a Primary Standard for Absorbed Dose Measurements in Beta Radiation Fields. Ph.D. thesis. Center for the Development of Nuclear Technology, CDTN / CNEN, Belo Horizonte, Brazil. (In Portuguese).